VLBI Observations of a Complete Sample of Radio Galaxies
IV-The Radio Galaxies NGC2484, 3C109 and 3C382.

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Summary

We present here new VLBI observations of one FR-I radio galaxy (NGC2484) and two Broad Line FR-II radio galaxies (3C109 and 3C382). For 3C109 new VLA maps are also shown. These sources belong to a complete sample of radio galaxies under study for a better knowledge of their structures at parsec resolution. The parsec structure of these 3 objects is very similar: asymmetric emission which we interpret as the core plus a one-sided jet. The parsec scale jet is always on the same side of the main kpc-scale jet. The limit on the jet to counterjet brightness ratio, the ratio of the core radio power to the total radio power and the Synchrotron-self Compton model allow us to derive some constraints on the jet velocity and orientation with respect to the line of sight. From these data and from those published on 2 other sources of our sample, we suggest that parsec scale jets are relativistic in both FR-I and FR-II radio galaxies and that pc scale properties in FR-I and FR-II radio galaxies are very similar despite of the large difference between these two classes of radio galaxies on the kpc scale.

Subject Headings: Radio Continuum: Galaxies; Galaxies: Nuclei; Galaxies: Jets; Galaxies: Individual by Name (NGC2484, 3C109, 3C382, NGC315, 3C338); techniques: interferometric

1. Introduction

The knowledge of the structure of radio galaxies on the parsec scale is relevant to test current models on jet dynamics and obtain new information to confirm the proposed radio source "unified schemes". Unification models suggest that FR-I radio galaxies (see Fanaroff and Riley 1974 for the definition of FR-I and FR-II radio galaxies) are the parent population of X-ray and radio selected BL Lac objects. The distinction between the three classes may correspond to different angles of the beamed emission with respect to the line of sight. Similarly, FR-II radio galaxies may be the parent population of steep spectrum, lobe-dominated radio quasars and flat spectrum, core-dominated quasars (Orr and Browne, 1982; Barthel, 1989; Ghisellini et al., 1993; Antonucci, 1993).

To test these models and to get new insight on the knowledge of radio galaxies on the parsec scale, we undertook a project of VLBI observations of a complete sample of radio galaxies, selecting from the B2 and 3CR galaxy samples those objects with a core flux density greater than 100 mJy at 6 cm at arcsecond resolution. This sample was presented in Giovannini et al. (1990 - Paper I) and consists of 27 radio galaxies: 15 belong to the FR-I class, 5 to the FR-II class and 7 are unresolved or slightly resolved at the arcsecond resolution. The core flux limit, imposed by observational constraints, could in principle produce a sample biased towards objects with the core flux density enhanced by Doppler boosting. Therefore we could have a larger number of objects with jets pointing towards the observer. This point is not important in discussing the single objects but will be taken in account and better discussed in the future when we will consider the statistical properties of the whole sample.

VLBI mapping and analysis of the radio galaxies of the sample is in progress. A detailed study on the radio galaxy NGC315 (Venturi et al, 1993; paper II) and 3C338 (Feretti et al., 1993; paper III), have been published. Here we present new VLBI observations on 3 more radio galaxies of our sample: NGC2484, 3C109 and 3C382.

In this paper we use a Hubble constant $H_0 = 100$ km sec^{-1} Mpc^{-1} and $q_0 = 1$.

2. The Sources

2.1 NGC2484

The radio galaxy NGC2484 (B2 0755+37) is a bright E galaxy ($M_v = -21.9$) with a redshift of 0.0413 (Colla et al. 1975), which gives the following linear size conversion: 1 milliarcsecond (mas) corresponds to 0.57 parsec (pc). At arcsecond resolution, it shows a flat spectrum core with two extended lobes in position angle (PA) 110° and it is classified as a FR-I radio source. Its total radio power at 408 MHz is 1.10×10^{25} W/Hz while the radio power of the arcsecond core at 5.0 GHz is 3.55×10^{23} W/Hz. An obvious jet is imbedded in the SE lobe. At higher angular resolution, a very short jet is also visible in the North-West (NW) direction. It is well collimated at the beginning, but it widens at a short distance from the nucleus to form the radio lobe (de Ruiter et al. 1986; Parma et al. 1987). The radio emission is highly polarized at 1.4 GHz

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(up to 30%) and the bright jet points to the more polarized lobe (Capetti et al. 1993) suggesting that the main jet is oriented towards the observer and that its luminosity is enhanced by Doppler effects (Parma et al., 1993). The arcsecond core flux density was monitored for 5 years (Ekers et al., 1983), but no variability was found.

For this galaxy we present new VLBI data at 6 cm.

2.2 3C109

The radio source 3C109 has been identified with an isolated, Broad Line N galaxy (Grandi and Osterbrock, 1978), with a redshift of 0.3066 (Goodrich and Cohen, 1992) and M_v = -22.9. The linear size conversion is 2.6 pc/mas. A recent optical observations (Goodrich and Cohen, 1992) have suggested that its nuclear emission is obscured by dust. According to these authors, if the nucleus were seen unobscured, the surrounding galaxy would not be visible because of the very strong nuclear light and 3C109 would be classified as an intrinsically bright quasar. It is dimmed along the line of sight by intervening dust and the relativistic beamed structure should not lie close to the plane of the sky.

The presence of high internal absorption in 3C109 is confirmed by recent ROSAT X-ray observations presented by Allen and Fabian (1992). In fact, they find an excess column density associated with the AGN of $\sim 5\times10^{21}$ atom cm^{-2} (redshift-corrected). This value is consistent with the reddening observed in optical studies. Therefore the interpretation of the nature of 3C109 is shared by Allen and Fabian (1992), who conclude that 3C109 is identical to luminous steep spectrum quasars and it is classified as a galaxy due to its intrinsic absorption. They suggest an intermediate angle of $\sim 50°$ between the radio axis of 3C109 and the line of sight assuming that the X-ray absorption is due to a torus of obscuring material surrounding the AGN with its symmetry axis along the radio axis.

The large scale radio structure consists of two very symmetric lobes with hot spots and core radio emission. It is a typical FR-II radio galaxy; the total radio power at 408 MHz is 1.32×10^{27} W/Hz (it has the highest radio power in our sample) and the arcsecond core radio power at 5.0 GHz is 1.32×10^{25} W/Hz (Giovannini et al., 1988). The flux density ratio between the two lobes is 1.0 ± 0.1 and the distance ratio between the core and the two hot spots is 1.00 ± 0.03.

The arcsecond radio core showed variability in the range 180 - 400 mJy (Ekers et al., 1983) in the period 1974 - 1980. Simultaneous observations with the Very Large Array (VLA) by Antonucci (1988) at 6 and 1.3 cm, give a flux density at 6 cm of 234.5 mJy with a spectral index $\alpha_6^{1.3} = 0.26$ (S$(\nu) \propto \nu^{-\alpha}$). Evidence for variability at optical and near-infrared wavelengths has been reported by Rudy et al. (1984); Allen and Fabian (1992) report long term X-ray variability.

We observed 3C109 with VLBI at 6 cm to investigate the jet morphology in the inner parsec region. We also present VLA observations obtained to compare the parsec and kiloparsec scale radio morphologies. These VLA observations also reveal the polarization structure of the two lobes.

2.3 3C382

The radio source 3C382 (B2 1833+32) is identified with a D3 type galaxy (Matthews et al., 1964). Optical spectrophotometry by Osterbrock et al. (1976) shows that the nucleus has a high-excitation forbidden-line spectrum with redshift z=0.0578 superimposed on broad permitted lines and a strong continuum, typical of a Broad Line Radio Galaxy. It is peculiar in possessing very broad (FWHM $\sim$ 30000 km s^{-1}) emission lines (Tadhunter et al., 1986). Its optical magnitude is M$_v$ = -22.2. For this galaxy the linear size conversion is 0.76 pc/mas.

Exosat X-ray observations showed a doubling time of the X-ray flux of 3 days, consistent with the general correlation of X-ray luminosity with variability time scale for Seyferts and QSO's (Kaastra et al., 1991 and references therein).

On the arcsecond scale its radio structure consists of a compact, flat spectrum core coincident with the galaxy and two radio lobes aligned in PA $\sim$55° (Strom et al. 1978, Leahy et al. 1991, Black et al., 1992). The total radio power at 408 MHz is 5.01$\times$10^{25} W/Hz and it shows the classical morphology of FR-II radio galaxies. In the north-eastern lobe a faint jet is visible on the gray-scale map given by Black et al. (1992). The jet is not straight from the core to the hot spot, but shows a gradual bend. On the other side of the core no jet-like structure has been detected.

3C382 is known to be variable at X-ray (Barr and Giommi 1992 and references therein), radio (Strom et al. 1978), optical (Puschell 1981) and ultraviolet (Tadhunter et al. 1986) wavelengths. In the radio regime Strom et al. (1978) report a flux density decrease from 230 mJy to 175 mJy in the period 1972.5 - 1974.3; Ekers et al. (1983) however, found a constant core flux density of 206 $\pm$12 mJy in the period from 1976.0 to 1980.2.

We present here new VLBI observations at 2.3 and 8.4 GHz of the nuclear region of this galaxy. At 8.4 GHz a high resolution map is available while at 2.3 GHz only a model fit to the visibility data is possible due to the lack of data in many baselines (see Sect. 3.1).

3. Observations and Data Reduction

3.1 VLBI data

The observational details for each source are given in Table 1: source name (col. 1), observing frequency (col. 2), observing mode and bandwidth (col.3 and 4 respectively); telescopes and observing dates (col. 5 and 6 respectively).

For the sources NGC2484 and 3C109, after the data correlation and fringe search, the output visibilities were written in FITS format. Initially the visibility amplitudes were calibrated using the gain values and system temperatures provided by the antenna during the observations. Later the gain values were checked, and when necessary corrected using standard VLBI calibrator sources assumed to be unresolved by the European and US baselines. The calibrator flux density was measured during the observations at the Effelsberg and Owens Valley telescope. The corrections to the given antenna gains were always $\lesssim$10%. The calibrated data were global fringe fitted in AIPS and reduced using the AIPS package with the standard procedure: as a first step the data were edited to delete the bad points. A map was preliminary

obtained whose clean components were used as the input model for the phase self-calibration cycle. When good agreement between the data and the source model was reached and phases were stable, we allowed gain self-calibration with 2 hours time scale to correct amplitude calibration errors.

The radio galaxy 3C382 was observed at 2.3 and 8.4 GHz simultaneously. The experiment consisted of observations of the quasar 3C395 phase-referenced to the core of 3C382. The switching duty cycle between the two sources only allowed for scans shorter than 5 minutes on 3C382 which, however, were well spread in the u-v plane. At Effelsberg and the VLA only the 8.4 GHz receiver was available (see Table 1). After the global fringe fitting the data were exported to Caltech package format for mapping purposes (Pearson, 1991) and to a format compatible with the astrometric program VLBI3 (Robertson, 1975). The astrometric part of the work will be reported elsewhere (Lara et al., in preparation). Standard calibration, editing and hybrid mapping procedure were used to obtain our final image.

At 2.3 GHz 3C382 was detected only on the two baselines Noto-Medicina and Medicina-Onsala due to technical problems and the low correlated flux density. Therefore, only model fitting to the data on these baselines was possible at this frequency.

3.2 VLA data

The radio galaxy 3C109 was observed with the VLA in A and B configurations at 1.4 GHz and in B and C configurations at 4.9 GHz in 1982 and 1983, in the same observing sessions as reported earlier for 3C411 (Spangler and Pogge, 1984) 3C79 and 3C430 (Spangler et al., 1984). Details of the VLA observations may be found in those papers. Maps were obtained combining the A and B arrays at 1.4 GHz and the B and C arrays at 4.9 GHz to have the same UV-coverage at the 2 frequencies. We obtained also a 6 cm map in the A configuration using the data recorded at the VLA during VLBI observations. The data were calibrated in the standard way using the AIPS package. We observed 3C48 as gain calibrator just before the start of the VLBI session. The calibrator source 0406+121 was observed every 30 minutes to phase the array. The final map was obtained synthesizing a large field (2048×2048 pixels) due to the large size of 3C109. Data were first edited and then self-calibrated for phase and amplitude. In the final map, the noise level is 0.05 mJy/beam with a resolution of 0.55 arcsecond (HPBW). For technical reasons, no polarized data are available at this resolution. An attempt to combine these data with previous 4.9 GHz data, to obtain a high resolution map with a good uv-coverage also at the short baselines (A+B+C configurations), was not possible due to problems in homogenizing the data and to the variability of the core flux density.

4. Results

Figure 1 shows the final uv coverage for all the 3 sources, except for the data on 3C382 at 2.3 GHz. In Table 2 some VLBI observational parameters and results are summarized for each source; columns 1 - 9 contain: the source name and the observing frequency (col. 1 and 2), the synthesized HPBW, the major axis PA and the noise

level (col 3, 4 and 5), the total VLBI flux density and the core flux density (col 6 and 7) and the jet flux density and PA (col 8 and 9 respectively).

4.1 NGC2484

A contour plot of the VLBI map is shown in Fig. 2, at full resolution (2a) and with a slightly super-resolved and round beam (2b). At parsec resolution NGC2484 shows an elongated radio structure. No spectral index information is available, however on the basis of the flat spectrum of the arcsecond core ($\alpha_{5.0}^{1.4} = 0.07$), we can reasonably assume the parsec scale core as coincident with the brightness peak in the VLBI map. In this case, the morphology is asymmetric with an extended feature oriented in PA 118° ±4°. This feature is not in agreement with the jet definition given by Bridle and Perley (1984). However, due to the source structure similarity with other parsec scale structures and being the small jet oriented as the main kpc scale jet, we interpret it as a one-sided jet. The jet-counterjet brightness ratio is $\gtrsim$20 at 2 mas from the core. The total flux in the VLBI map is 216 mJy (see Table 2), in good agreement with the correlated flux density in our shortest baseline. The core flux density at the arcsecond resolution is 195 mJy (see Giovannini et al., 1988). The discrepancy is within the uncertainties present in the VLBI flux scale calibration (10%). We have deconvolved the VLBI structure with 2 Gaussians to derive the core flux density. We estimate that the parsec scale core has a flux of ∼140 mJy which matches with the correlated flux density in the longest baselines (e.g. Effelsberg-Owens Valley). The jet PA in the VLA map is 110°±2° (marginally different from the pc scale jet PA (118° ±4°)).

4.2 3C109

4.2.1 Large Scale Structure

In Figures 3 and 4 the 1.5 arcsecond maps obtained at the VLA at 20 and 6 cm, respectively, are shown. On the 6 cm map the polarization vectors are superimposed. In Figure 5 the map obtained at the VLA with a resolution of 0.55 arcsecond, using the A configuration is shown. Note that the maps in Figures. 3 and 4 have been rotated by 55° for display purposes.
The projected linear size of 3C109 from our maps is ∼ 280 kpc. The hot spots are clearly visible and substructures are present in the 2 lobes. The distance of the two hot spots from the core is the same. A faint jet is present in the South-Eastern (SE) direction connecting the core to the SE lobe. The jet is well defined near the core and within the SE lobe but is only marginally detected in the region between the core and the hot spot. The jet is not straight, but near the core it oscillates (±10°) around the PA 150° while in the lobe it starts to bend to reach a final PA (near the hot spot) of ∼90°. No jet-like feature is visible on the other side of the source core. The jet-counterjet brightness ratio is $\gtrsim$24 at 1 arcsecond from the core. The low resolution maps confirm the symmetry in size found in the high resolution map, and show an extended low brightness region between the core and the hot spots.

The radio structure of the two hot spots is very interesting (Fig. 5). The SE one is the most compact in agreement with Laing (1989) who noted that compact hot spots are seen only on the jetted side of FR-II radio sources; two secondary knots, which mark the path of the jet, are present at ∼4 and 10 arcsecond of distance from the main

hot spot. The NW hot spot is elongated perpendicularly to the hot spot-core direction; a 'S' shaped structure is visible inside the inner region of the lobe.

We used the maps obtained combining the A and B arrays at 1.4 GHz and combining the B and C arrays at 4.9 GHz to derive the polarized flux from 3C109. In Table 3 we present the total flux density and the polarization percentage, derived from the maps with HPBW = 1.5 arcsecond at 6 and 20 cm; values are given for: the whole southern (col. 1) and northern (col. 5) lobe, the hot spot regions (defined as the regions where radio emission is visible in the high resolution map shown in Fig. 5; col. 2 and 6), the diffuse regions (col. 3 and 7) and the core (col. 4). The two hot spot regions are polarized at a level of 10% while no polarized flux is visible within the errors in the diffuse regions and in the core source. The polarization percentage is the same in the two lobes at the two frequencies; also the PA of the polarized vectors does not change. This result is only apparently in contradiction with the Laing-Garrington effect (Laing 1988; Garrington et al., 1988) and the suggestion (see Sect. 2.2) that 3C109 is not on the plane of the sky. In fact Garrington and Conway (1991) estimated for a typical depolarizing halo a core radius of ~ 100 kpc for low redshift (z < 1) sources. Since we detect a polarized flux only in the external regions of this double source, given the large projected size of 3C109 (280 kpc), we can reasonably assume that the polarized radio lobes are outside the more dense regions of the galaxy corona of hot gas responsible of the depolarization. Therefore we do not see the Laing-Garrington effect in 3C109 simply because the polarized flux comes from regions external to the halo surrounding 3C109 (if any). This is consistent with the anticorrelation found by Garrington and Conway (1991) between the depolarization asymmetry and the source linear size.

4.2.2 Parsec Scale

The contour plot of the 4.9 GHz VLBI image at full resolution is shown in Fig. 6a. Parameters of the radio source are given in Table 2. At VLBI resolution 3C109 shows a one-sided morphology, with a bright core extended in PA 130 $°\pm 5°$, and a faint knot of radio emission aligned in the same direction. This feature is more obvious in a super-resolved map, convolved with a round beam (Fig. 6b). Although this knot does not match all the criteria necessary to classify it as a jet (Bridle and Perley, 1984), it is certainly related with the existence of a jet, then we consider plausible to assume that on the parsec scale 3C109 has a one-sided core-jet structure. The jet is faint and slightly misaligned with respect to the kpc scale jet. The jet/counterjet brightness ratio is $\gtrsim 7$ at ~ 2 mas from the core.

The total flux density in the parsec scale structure is in good agreement with the core flux density measured in the VLA map obtained in the same epoch. We point out that our VLBI observations were made when the core flux density was at a minimum (~ 180 mJy).

4.3 3C382

In Figure 7 we present the 8.4 GHz VLBI image of 3C382. The total flux density of the VLBI structure is 190 mJy with a compact core of 115 mJy.

The VLBI structure of 3C382 presents a core-jet morphology with marked wiggles: the jet extends in PA $\sim 40°$ for ~ 1 mas, then in PA $\sim 90°$ up to ~ 3 mas from the core and finally again in PA $\sim 40°$. In Table 2 we give the map parameters. The

jet/counterjet brightness ratio is $\gtrsim$30 at ~2 mas from the core.

The parsec scale jet is on the same side of the faint kpc-scale jet visible on the map given by Black et al. (1992). The kpc-scale jet PA is $\sim 50°$, but, as in 3C109, an evident change in the PA is necessary to reach the hot spot (the final PA is 90°), confirming an instability in the jet position angle from the pc to the kpc scale in this source.

At 2.3 GHz the best model obtained from modelfitting the two baselines Medicina-Noto and Medicina-Onsala (see Sect. 3.1) gives a single Gaussian component of 157 mJy flux density and slightly extended in PA $\sim$50° consistent with the results at 8.4 GHz. An estimate of the overall spectral index between the two frequencies gives $\alpha \sim$ -0.1.

5. Discussion

The three radio galaxies presented here show similar parsec scale morphologies: a strong compact component, identified with the core, and a faint one-sided jet. In all cases the parsec scale jet is oriented on the same side of the kpc scale main jet. This correlation implies either that jets are intrinsically asymmetric or that parsec and kpc scale jets are relativistic.

The presence of relativistic jets in strong radio sources as quasars and FR-II radio galaxies is now widely accepted (see Antonucci 1993 for a recent review). Also, evidence is growing that radio jets in FR-I galaxies are initially relativistic. This is consistent with the recent result by Parma et al. (1993a) that in FR-I radio galaxies the stronger jet is generally on the same side of the less-depolarized lobe, just as in the FR-II radio sources. This is also consistent with the decrease of jet sidedness ratio with distance from the core and its trend with the total and core radio power examined by Parma et al. (1993b). Laing (1993) developed a two component model in which FR-I jets are relativistic on small (parsec) scales, but decelerate quickly and become non-relativistic on large (kpc) scales. This model explains the correlation between polarization and sidedness in FR-I jets.

Therefore we interpret the radio structures presented here as affected by Doppler favoritism and will use the available data to constrain the possible values of the intrinsic jet velocity and of the orientation of the radio source with respect to the line of sight.

We also include in the discussion the data on two previously studied sources belonging to our sample, i.e. 3C338 (Feretti et al., 1993) and NGC315 (Venturi et al., 1993). In Venturi et al. (1993) we took into account the possibility that the one-sided small scale morphology of NGC315 is caused by intrinsic asymmetries. As stated before, we adopt here the view that the jet is Doppler boosted. This is also suggested by Bicknell (1994) who modeled the radio jets of NGC315 assuming an initially relativistic velocity and deceleration by turbulent entrainment.

Including 3C338 and NGC315, our results concern two FR-II and three FR-I radio galaxies.

5.1 Jet Sidedness

Assuming that the jets are intrinsically symmetric, from the jet to counterjet brightness ratio R we can constrain the value of $\beta cos\theta$, according to the formula

$$R = (1 + \beta cos\theta)^{2+\alpha} \, (1 - \beta cos\theta)^{-(2+\alpha)}$$

where β is the ratio of the jet velocity to the speed of light and θ is the angle to the line of sight. The jet spectral index α is assumed to be 0.5 (Pearson and Zensus, 1987). The validity of this standard formula depends on the degree of isotropy of the intrinsic synchrotron emissivity in the jet (see Begelman, 1993). We may expect some anisotropy in the observed radiation depending on the degree of ordering and the magnetic field orientation. The measure of magnetic field properties may be derived from maps of the polarized flux at parsec resolution. In a jet with 20% polarized flux, the anisotropy due to the magnetic field will increase the beaming ratio by less than 30-50 %. The effect can be much more prominent in highly polarized jets ($\sim 50\%$) with an increase of a factor 2-3 in the beaming ratio (Begelman, 1993). In the following discussion we shall assume that the fractional polarization in the parsec scale jet is not too large, i.e. that the parsec scale jet emissivity is roughly isotropic. This assumption has to be tested in the future with VLBI maps of the polarized flux in a large sample of radio galaxies.

We have obtained the value of $\beta cos\theta$, from the VLBI jet and counterjet ratios. In the sources 3C109 and NGC2484 some brightness asymmetry is present also on the arcsecond scale. By assuming that this asymmetry still originates from Doppler boosting, the factor $\beta cos\theta$ can be constrained also on this scale. In particular the constraint on the arcsecond scale for 3C109 is stronger than that on the parsec scale owing to the better signal to noise ratio of the VLA map. Since we do not consider a jet reacceleration from the parsec to the kpc scale, for this source we will adopt the limit on $\beta cos\theta$ derived from the VLA map for both scales. For NGC2484 the arcsecond constraint is in agreement with a jet deceleration from the parsec to the kpc scale. No discussion is possible on the kpc scale jet of 3C382 for the lack of a jet counterjet ratio on this scale.

The obtained values of $\beta cos\theta$ are summarized in Table 4 which is organized as follows: col. 1 the source name, cols. 2, 3 and 4 respectively the VLBI jet to counterjet brightness ratio R, the parsec-scale limit to $\beta cos\theta$ and the distance 'd' in milliarcsecond between the core and the region where R was estimated; cols. 5,6 and 7 the same values from the VLA maps with the distance in arcsecond. In Fig. 8 the allowed region in the $\theta - \beta$ space is shown.

5.2 Core Radio Power

Given the existence of a general correlation between the core and the total radio power in radio galaxies (Giovannini et al., 1988), we can derive an expected intrinsic core radio power from the total galaxy radio power. Since the total radio power is measured at low frequency and is therefore not affected by Doppler boosting, the core emission implied by the total radio power is not boosted. Objects with a core radio power stronger than the expected value could be interpreted as galaxies where the core radio emission is contaminated by a Doppler boosted relativistic jet lying close to the line of sight. Therefore a constraint on $\beta cos\theta$ can be derived independently from the jet sidedness. Giovannini et al. (1988) found the following correlation between the arcsecond core radio power P_c and the total radio power P_t using a sample of 187 radio galaxies selected at low frequency:

$$\text{Log } P_c = 11.01(\pm 1.05) + 0.47(\mp 0.4)\text{Log} P_{tot}$$

We expect that the radio galaxies used to derive the previous correlation are at different angles with respect to the line of sight and have an uniform distribution being selected at low frequency. In this case the dispersion of P_c around the best fit value reflects the different orientation to the line of sight. Assuming that sources are oriented at random angles, the best fit value corresponds to the average orientation angle (60°) with respect to the line of sight and the previous correlation should be read as:

$$\text{Log } P_c(60) = 11.01 + 0.47 \text{Log} P_{tot}$$

where $P_c(60)$ is the apparent (beamed) core radio power for a galaxy oriented at 60° with respect to the line of sight. Since the Doppler enhancement in a jet oriented at an angle θ is:

$$P_c(\theta) = P_i \ (1 - \beta cos\theta)^{-(2+\alpha)}$$

where P_i is the intrinsic radio power and $P_c(\theta)$ is the apparent (beamed) radio power, assuming $\alpha = 0$ for the core emission, we finally obtain:

$$\beta = (K - 1) \ (K \ cos\theta - 0.5)^{-1}$$

with $K = [P_c(\theta)/P_c(60)]^{0.5}$. We used this correlation to derive upper and lower limits to β and θ, taking into account the statistical uncertainties (1 σ) and a possible core flux density variability up to a factor of 2. The derived values are drawn in Fig. 8.

We point out that in the above argument the core flux density measured on the arcsecond scale is used. A better estimate of the beaming factor of the core could be obtained using the VLBI core flux density, but the main problem to do this is that the correlation between the total radio power and the milliarcsecond core radio power is poorly known and still affected by large uncertainties. In our Paper I (Giovannini et al., 1990) we derived this correlation for 20 objects and we found it to be consistent within the errors with the one used in the present discussion.

5.3 The Synchrotron-self Compton emission

Independent constraints on the amount of beaming for a radio source can be derived from the Synchrotron-self Compton (SSC) model of X-Ray emission from the nuclear region (see Marscher, 1987; Ghisellini et al., 1993). In principle, when the core angular size is known, the comparison between the predicted and observed X-Ray flux density gives a lower limit to the Doppler factor δ defined as:

$$\delta = [\gamma(1 - \beta cos\theta)]^{-1}$$

where $\gamma = (1 - \beta^2)^{-1/2}$.

We derived δ using the Ghisellini et al. (1993) formula assuming that the core emission is due to a partially opaque electron synchrotron radiation from a uniform sphere and that $\alpha = 0.5$ for the thin synchrotron emission. The parameters entering in the computation are given in Table 5 as follows: redshift, VLBI core size D_{VLBI}, radio flux F_m at the self absorption frequency ν_m and X-Ray flux F_x at the energy $h\nu_x$. We want to note that the derived values of δ, given in Table 5, are crude estimate due to the uncertainties in the knowledge of the self absorption radio frequency, the core angular size and the X-Ray flux. In particular, the X-Ray flux can be overestimated due to the contamination of a thermal component which is found to be present in radio galaxies (see e.g. Worral and Birkinshaw, 1994). For this reason we use the Einstein HRI flux when available (only for NGC315).

Lower limits of δ obtained here, are in agreement with those given in Ghisellini et al. (1993) for radio galaxies and lobe-dominated quasars confirming that radio galaxies

have much smaller δ than compact quasars. Only for NGC315 the lower limit of δ is > 1 allowing us to constrain β and θ (see Fig. 8). For the other sources the derived lower limits are not conclusive.

5.4 Implications on the jet velocity and orientation

The implications on the jet velocity and orientation come from the constraints obtained in Sect. 5.1, 5.2 and 5.3. For each source we also imposed an upper limit on the angle to the line of sight θ, to restrict the maximum intrinsic radio source size to 1.5 Mpc.

As discussed before, a larger range of allowed values is possible from the jet/counterjet brightness ratio if we assume that some anisotropy, due to the directionality of the magnetic field, is present in the intrinsic synchrotron jet emissivity (Begelman, 1993). However, we note that in our sources the major constraint to the values of β and θ is obtained from the dominance of the radio core on the extended radio emission.

While it seems difficult to further improve the constraints on β and θ from the ratio $P_c(\theta)/P_c(60)$, due to the flux density variability of the radio galaxy cores, we expect to derive stronger constraints in the future from the ratio between the jet and counterjet brightness, which is presently limited by the noise level in the maps. Thanks to the better sensitivity reachable now with the global array (European VLBI Network + Very Long Baseline Array), we should obtain maps with a noise level low enough to put stronger constraints on β and θ. Moreover high resolution X-Ray data from the Rosat satellite could be helpful for the application of the SSC model.

From a careful analysis of figure 8, we can summarise our results as follows:
- the allowed range of θ is $10° < \theta < 35°$ for 3C109. This result confirms even at radio frequencies that 3C109 is an obscured quasar as suggested by X-Ray and optically observations (see Sect. 2.2). This is in agreement with the prediction of unified models where lobe dominated broad line radio galaxies are interpreted as lobe dominated QSS which appear as galaxies only because nearby (see e.g. Antonucci, 1993) and therefore are expected to be at $10° < \theta < 40°$ with respect to the line of sight (see e.g. Ghisellini et al., 1993). In the case of 3C382, which is a lobe dominated broad line radio galaxy as 3C109, our constraints are not as strong as for 3C109 and the allowed range of θ is $5° < \theta < 48°$;
- for NGC315 the allowed range of θ is narrow ($30° < \theta < 41°$). This range is fully consistent with the unification schemes, which predict FR-I radio galaxies to be at angles $\theta \gtrsim 30°$ to the line of sight (see e.g. Ghisellini et al., 1993). For NGC2484 instead the present data cannot exclude angles $< 30°$;
- the case of 3C338 is rather peculiar due to the symmetry of the radio structure: all angles are allowed even if small orientation angles imply low jet velocities;
- the possible range of β is $0.8 \lesssim \beta \lesssim 1$ for NGC315 and 3C109 and $0.6 \lesssim \beta \lesssim 1$ for NGC2484 and 3C382. For 3C338 we derive lower values of β infact either the source lies in the plane of the sky and $\beta \lesssim 0.4$ or the jets are not relativistic and all angles are allowed. We note however that the β upper limit for 3C338 derives from the ratio between the core and total radio power and that the 3C338 core emission is strongly variable (see Feretti et al., 1993). Therefore the uncertainty from the core - total radio power correlation may be larger than the one taken in account here.

No reliable map at a different epoch is presently available to search for a possible superluminal motion in these sources. Assuming a high jet velocity ($\beta \lesssim 1$) we expect for these sources a proper motion $\lesssim 1$ mas/yr. Observations have been already planned and will give soon useful data to discuss this point.

We also note that at parsec resolution we do not see any difference between FR-I and FR-II radio galaxies. In both classes of sources, the observed radio structures are very similar and may be explained assuming that parsec scale jets are relativistic. Data on more radiogalaxies are necessary to confirm this similarity between FR-I and FR-II radio galaxies on the parsec scale and to study possible correlations between the nuclear power, the jet velocity and the large scale radio morphology. However, this similarity could indicate that the large morphological difference between FR-I and FR-II radio galaxies on the kpc scale is due to a different interaction of the jet with the surrounding medium on a scale larger than the VLBI one.

We finally wish to comment on the flip-flop model, which was invoked as a possible interpretation of the structure of 3C338 (Feretti et al., 1993). No evidence in favour of this model was found in other sources studied so far. Therefore it seems that even in the case that the jets are fed by an alternate ejection, the jet speed must be relativistic to account for the one-sidness of the source structures on the parsec scale.

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Figure Captions

Fig. 1: uv-coverage of VLBI observations. A) NGC2484; B) 3C109 C) 3C382 at 3.6 cm

Fig. 2a: VLBI image of NGC2484 at 5.0 GHz. The HPBW is 1.50×0.74 mas in PA -18°. The noise level is 0.5 mJy/beam. The bar on the left corner is 1 pc. Contour values are: -1,1,2,3,4,5,7,10,15,20,30,50,100,150 mJy/beam.

Fig. 2b: The same as Fig. 2a but super-resolved in declination; the HPBW is 1×1 mas. The bar on the left corner is 1 pc.

Fig. 3: VLA image of 3C109 at 1.4 GHz. The HPBW is 1.5 arcsec; the noise level is 0.2 mJy/beam.
Contour levels are: -0.5,0.5,1,1.5,2,3,4,6,8,10,20,30,50,70,100,150,200,250,300,400, 600 mJy/beam. The map have been rotated by -51°.

Fig. 4: VLA image of 3C109 at 4.9 GHz with superimposed polarization vectors. The length of polarized lines is proportional to the polarization percentage at 5.0 GHz. The HPBW is 1.5 arcsec; the noise level is 0.15 mJy/beam.
Contour levels are: 0.3,0.5,1,5,10,50,200 mJy/beam. The map have been rotated by -51°.

Fig. 5: High resolution VLA image of 3C109 at 5.0 GHz. The HPBW is 0.55 arcsec. The noise level is 0.05 mJy/beam; contour levels are: -0.15,0.15,0.3,0.5,0.7,1,1.5,2,2.5,3,10,30,50,100,150 mJy/beam. The bar on the right corner is 50 kpc.

Fig. 6a: VLBI image of 3C109 at 5.0 GHz. The HPBW is 3.0×0.8 mas in PA 165°. The noise level is 0.7 mJy/beam. Contour levels are: -1.5,1.5,3,5,7,10,20,30,50,100,150 mJy/beam. The bar on the left corner is 5 pc.

Fig. 6b: The same as Fig. 6a but super-resolved in declination; the HPBW is 1×1 mas. The noise level is 0.5 mJy/beam. Contour levels are: -1.0,1.0,2,3,4,6,8,10,30,50,100,150 mJy/beam. The bar on the left corner is 5 pc.

Fig. 7: VLBI image of 3C382 at 8.4 GHz. The HPBW is 2.0×0.5 mas in PA -6°. The noise level is 0.5 mJy/beam. The bar on the left corner is 1 pc.
Contour levels are: -1.0,1.0,1.5,2,2.5,3,4,6,8,10,15,30,50,70 mJy/beam.

Fig. 8: Constraints on the angle θ, between the jet and the line of sight, and the intrinsic jet velocity β. Curves are as following: 'A' from the jet/counterjet ratio; 'B' from the core flux density (see Sect. 5); 'C' from assuming an intrinsic maximum linear size of 1.5 Mpc; 'D' from the SSC model. The allowed region is the undashed one. Curve C has not been drawn for NGC2484, 3C338 and 3C382 due to the small projected size of these sources. The allowed region is $> 5°$ for 3C382 and $> 2°$ for the other two sources.